The International Journal of Advanced Manufacturing Technology (2023) 128:1077–1087
https://doi.org/10.1007/s00170-023-11837-9

ORIGINAL ARTICLE

Machining grade 4 titanium alloy by minimum quantity lubrication for enhanced sustainable manufacturing

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Received: 1 March 2023 / Accepted: 22 June 2023 / Published online: 24 July 2023

Abstract

Machining is a widely used class of industrial manufacturing operation, wherein cutting fluids play a vital role in terms of machining accurate dimensional quality objects due to their cooling, lubricant, and chip removal abilities. Although certain advanced cutting fluids have changed the manufacturing industry for the better, there are some environmental concerns associated with some of these fluids. The use and disposal of cutting fluids may be costly and subjected to stringent government laws. Hence, the ever-growing research conducted on environmentally friendly cutting fluids may lead to enhanced sustainable manufacturing. The aim of this investigation is therefore to investigate the viability of minimum quantity lubrication (MQL) during machining of titanium alloys with specific focus on the commercially pure grades (grade 4). A comparative study was conducted in order to establish the effects of different modes of lubrication, i.e., dry, wet, and MQL machining on titanium.

Keywords Titanium · Minimum quantity lubrication · Dry machining · Wet machining sustainable manufacturing

1 Introduction

Titanium and its alloys enjoy significant use in the marine, chemical, mechanical, and aeronautical industries despite the complications involved during the extraction process, melting process, and problems encountered during machining and manufacturing [1]. This is largely attributed to their mechanical properties that include low density, high hot strength and hardness, superior fracture toughness, and corrosion resistance. The most widely utilized titanium alloy is grade 5 or Ti6Al4V along with several variants. This is due to its high strength, low density, and general availability. Commercially pure or CP titanium alloys are also widely used but are typically utilized in applications where high strength may not be the most important property. Grade 4 is considered to have the highest strength as compared to the other commercially pure titanium grades. It has excellent corrosion resistance in many adverse environments, adequate strength, and good formability. It is most commonly utilized in the chemical sectors, marine environments, and in medical tool and implant applications. In these applications, corrosion resistance coupled to low density and adequate strength (still relatively high) are typically required.

Titanium alloys are generally considered to be difficult-to-machine materials [2]. Their high strength and hardness can lead to significant tool failure resulting from excessive compressive stresses on the cutting tool [2]. Their low thermal conductivity limits titanium alloys from dissipating heat from the cutting interface via the removal of cutting chips and conduction into the workpiece material. Thus, the heat created when machining concentrates at the cutting interface which leads to excessive localized temperatures [3]. When machining titanium alloys at a cutting speed of 75 m/min, the distribution of the temperature of the cutting tool is similar to that of machining carbon steel at a cutting speed of 240 m/min [3]. This expedites tool failure, thus resulting in abrasion, diffusion, and plastic deformation [4]. Moreover, the intense heat gradient, which results from the small heat-affected zone due to the shorter tool-chip contact length, results in high chipping mainly when utilizing a higher cooling capacity coolant, i.e., water-based cutting fluid [5].

Conventional cutting fluids are considered to be the lubricant/coolant of choice during machining because of their ability to address the heat generated at the cutting interface

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[6]. Cutting fluid use includes benefits such as cooling, chip removal, and lubrication of the cutting zone. However, there are several challenges linked with their application. The excessive utilization of these fluids and their inevitable disposal pollutes the environment and may be harmful to the machinist. Cutting fluids typically account for approximately 18% of the overall cost of machining intensive manufacturing. Thus, it is of utmost importance to investigate new techniques of machining titanium for high precision parts as used in a number of industries. Various alternative methods have been considered along with serval techniques to deliver the lubricant/coolant flow. Some scientists have focused on minimum quantity lubrication (MQL) as it reduces the use of coolant by delivering a combination of air and cutting fluid in an optimized manner into the cutting zone instead of wet machining. Minimum quantity lubrication also has the added benefit that it is more amenable with the conditions of "green" or sustainable machining. Effective or green manufacturing should ideally incorporate the social, economic, and the environmental aspects of the associated manufacturing process [7, 8].

Green manufacturing (GM) strives to enhance the eco-friendly properties of a manufacturing process. Environment compliance is one of the fundamentals of green manufacturing. Manufacturing industries are normally money-oriented. A profitless technological strategy would be a challenge to establish. Effective implementation of environmentally friendly machining (EFM) may in oftentimes be cost-effective when a cost management strategy is implemented [9]. To this end, the manufacturing of components with reduced or zero application of cutting fluids/lubrication along with an associated reduction in energy consumption may be of significant benefit.

Eliminating or minimizing the application of cutting fluids used during machining has been one of the most significant areas of interests towards environmentally friendly machining [10]. Conventional cutting fluids are utilized to reduce heat generation, to improve surface roughness and tool life, and to control chip formation [11]. However, these cutting fluids may contain hazardous chemicals that possess serious environmental risks [12]. A number of strategies are being investigated in an attempt to minimize the application of cutting fluids. These include solid lubrication, high-pressure coolant, gas/vapor cooling, liquid nitrogen cooling, and nanofluid-based machining [13]. MQL implies near dry machining and/or a minimal usage of lubricants. In general, conventional wet machining has many downsides such as high coolant consumption with the associated interaction with tooling, workpieces, and the human operator. MQL attempts to address some if not all of these drawbacks.

Pusavec et al. [9] conducted a comparative study to access sustainable production techniques during high-performance machining (turning) of a nickel-based alloy Inconel 718. They utilize four different lubrication/cooling techniques, i.e., dry, near-dry (MQL), cryogenic, and cryo-lubrication (cryogenic + near-dry). It was found that there is a notable reduction in tool failure, machining cutting force, and an improved surface finish during the machining by MQL which resulted in improved sustainable production in contrast to dry and cryogenic machining.

Park et al. [10] examined the machinability when utilizing minimum quantity lubrication and liquid nitrogen cooling when machining titanium and compared it to conventional machining. The aim was to establish the most effective and efficient lubrication and cooling technique for Ti-6Al-4V. It was found that MQL and LN cooling outperformed conventional machining and thus were the most promising technique regarding tool wear and chip morphology. Machining by MQL resulted in the lowest flank wear and lowest chip peak valley.

In order to illustrate the growing interest in MQL-assisted machining, Fig. 1 presents the trend of MQL-related research during the processing of titanium and its alloys in the last several years.

In this regard, current international research focuses largely on high-strength titanium alloys. Very little if any research is published on the benefits of MQL when machining commercially pure titanium grades. This paper, therefore, aims to investigate the feasibility of machining grade 4 titanium alloy by MQL and to directly compare it to conventional wet machining with a specific emphasis on sustainable manufacturing. Which entails:

(i) Reducing the consumption of hazardous cutting fluids by investigating the use of green lubricants and sustainable lubrication techniques.
(ii) Reducing the total cost involved during manufacturing by reducing tool wear, improving workpiece surface integrity, do away with the need for post-finishing operations, and reducing the energy consumption.
(iii) Overall machinability enhancement.

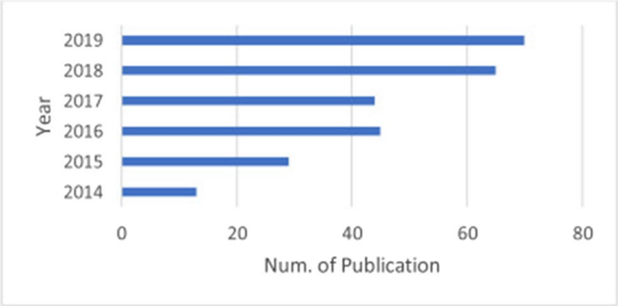


Fig. 1 MQL machining research published yearly from 2014 until 2019 [11]

The application of minimum quantity lubrication (MQL) can enhance the testing output in several ways:

MQL uses significantly less lubricant than conventional flood cooling techniques. As a result, there is less waste, oil consumption, and environmental impact. MQL is regarded as a more environmentally responsible and sustainable lubricating method.

MQL aids in lowering friction and heat by applying a minimum quantity of lubricant directly to the cutting zone during machining, thereby reducing tool wear and therefore tool changes which leads to improved productivity and cost savings. The reduction in friction and heat can also reduce undesirable effects such as workpiece distortion and metallurgical changes due to the formation of a heat-affected zone (HAZ) with altered material properties. This has beneficial effects on surface roughness and dimensional accuracy and therefore the surface integrity.

It is important to note that the specific benefits of MQL may vary significantly based on the application, tooling, cutting strategy, and lubricant choice. To maximize the advantages and improve a specific application, rigorous experimentation is required to optimize the MQL process parameters.

2 Experimental details

To successfully compare green machining to conventional machining, three different machining strategies (dry, wet, and MQL machining) will be investigated (see Table 1). The machining parameters are considered based on the work conducted by Mathonsi [14] on the optimization of the machining parameters for the turning process of titanium grade 4 using the Taguchi method. The optimum levels of the input machining parameters were identified according to the responses of a composition desirability value and based on an equal weighting of tool wear, surface roughness, power consumption, and cutting forces. A cutting speed of (v_c) 250 m/min, a feed rate (*f*) of 0.1mm/rev, and a depth of cut (*d*) of 1 mm yielded the maximum composite desirability value and were regarded to be optimum.

Similarly, MQL parameters were based on the work done by Mathonsi et al. [15]. The aim of this study was to understand the influence of core MQL parameters on the machinability of titanium grade 4 and to optimize the MQL parameters to facilitate sustainable machining. The experiments were conducted according to a Taguchi L9 orthogonal array which implies 3 different levels of MQL flow rate (50, 70, and 90 ml/h), nozzle distance (20, 30, and 40 mm), and air pressure of (4, 5, and 6 bar). TOPSIS and ANOVA were implemented in order to establish optimum parameters from the experimental results. The results from both these techniques found the optimal combination of MQL parameters to be a MQL flow rate of 70 ml/h, nozzle distance of 30 mm, and an air pressure of 4 bar. The results also showed that MQL flow rate is the most significant parameter followed by the nozzle distance and then the air pressure. A confirmation test was then conducted in order to validate the optimization process.

Table 1: Experiment parameters and machining conditions

Machining environment		
Dry	Wet	MQL
Machining parameters		
$v_c = 250$ m/min, $f = 0.1$ mm/rev, and $d = 1$ mm		
MQL parameters		
$M_{FR} = 70$ ml/h, $N_D = 30$ mm, and $N_p = 4$ bar		
Lubrication characteristics		
Pour point: 80 C, flash point: >2900 C, density: 0.9199 g cm^3 at 200 °C		

2.1 Output Parameters

In the present research work, the machining and MQL parameters will be fixed. Tool wear (*T*), surface roughness (*R*) power consumption (*P*), and cutting forces (*F*) are considered dependent variables. Three different machining environment will be considered, dry, wet, and MQL machining. The accuracy of the experiment was improved by running each measurement three times. Table 2 shows the different output parameters that will be measured during the experiment.

Table 2 Output parameters

Test	*T*	*R*		*P*	*F*		
	T_w	R_a	$R_{\max}$	P_o	F_x	F_y	F_z
1	X-1	X-2	X-3	X-4	X-5	X-6	X-7
2	X-8	X-9	X-10	X-11	X-12	X-13	X-14
3	X-15	X-16	X-17	X-18	X-19	X-20	X-21

Fig. 2 Workpiece (CP-Ti grade 4)

2.2 Experimental setup

2.2.1 Workpiece material and tooling

The turning experimentation utilized commercially available grade 4 titanium bars (75 mm diameter) as illustrated in Fig. 2. Table 3 presents the composition of the workpiece material as per the material certificate.

The turning tests were conducted using a rhombic uncoated carbide inserts (see Fig. 3a). An uncoated insert was specifically used to facilitate a more representative comparison of tool wear between the different cool techniques. A Sandvik tool holder (DCLNR 2020K 12) with quick insert clamping and release screw mechanism was used (see Fig. 2).

Table 3 Commercially pure titanium grade 4's chemical composition

CP-Ti	Chemical composition					
	Titanium	Iron	Hydrogen	Nitrogen	Oxygen	Carbon
Grade 4	Balance	.206	.0028	.0028	.3	.012

Fig. 3 Cutting tool and holder: **a** ISCAR cutting inset and **b** Sandvik tool holder (DCLNR 2020K 12)

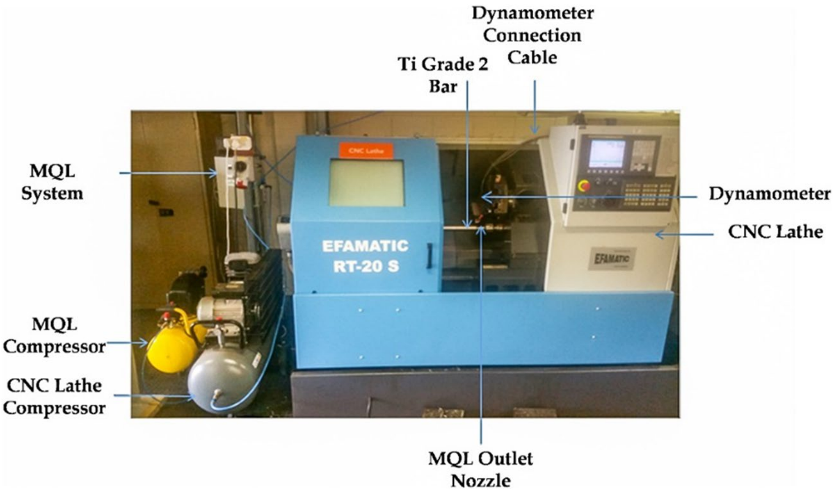


Fig. 4 Experimental setup used during the machining of CP-Ti grade 4

Fig. 5 Nozzle and the dynamometer positions

2.2.2 Turning

The turning process was performed on an Efamatic RT-20S CNC lathe that has a spindle motor of 15 kW and can reaches up to 4500 rpm (Fig. 4). For the MQL system, an external feed supply type Producut MQL system was used. This device can produce a flow rate up to 540 ml/h using Flexi lock line nozzles. The nozzle and the dynamometer positions can be seen in Fig. 5.

2.2.3 Measurements

Flank wear was measured by using Mitutoyo's tool maker's microscope, while the surface roughness (R_a and R_{max}) values were obtained using a handheld Hommel T500 roughness tester. During the experimentation, the power consumed by the different equipment/devices was measured using a KEW 6306 power meter. A Kistler quartz three-component piezoelectric dynamometer, type 9265B fitted with a tool holder for turning, was used for all force measurements. The tool wear was also investigated by scanning electron microscopy (Tescan Vega 3) (Fig. 6).

3 Results

A comparative evaluation between dry, wet, and MQL machining has been done. Table 4 presents the values of machinability indicators (tool wear, maximum roughness, power consumption, and cutting force) obtained in case of all machining conditions (dry, wet, and MQL).

3.1 Effect of lubrication techniques on tool wear

Flank wear is typically the most studied form of tool wear. It is also considered to be one of the most significant parameters when assessing the machinability of a material as it may progressively deteriorate the surface quality of the machined product. Other important machinability indicators include cutting force, surface roughness and energy use. A comparison of flank wear for the different cooling/lubricating

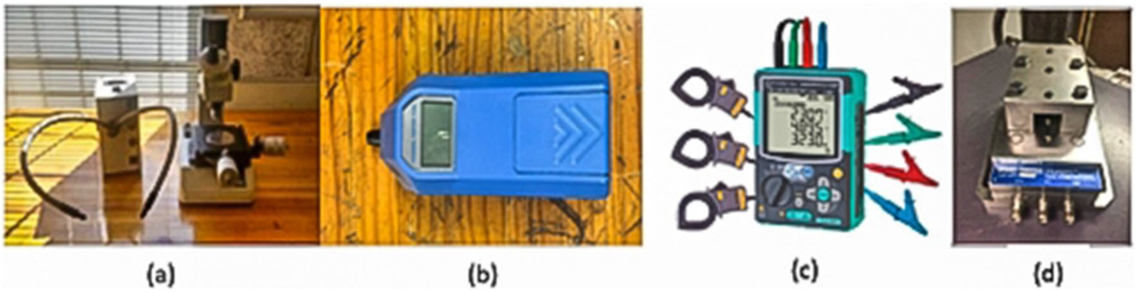
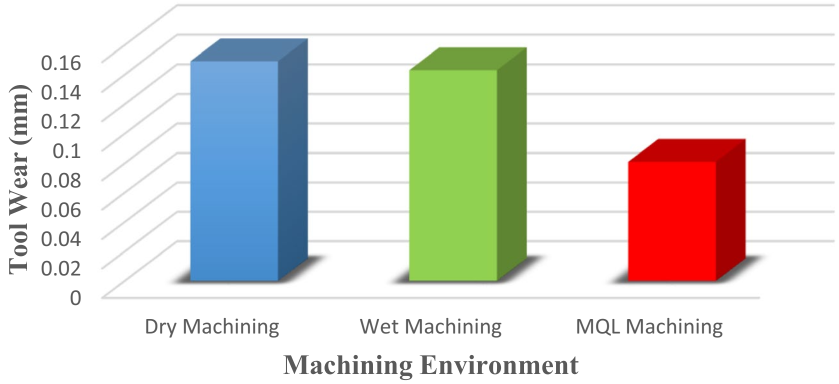


Fig. 6 Measuring equipment: **a** TM-510 Mitutoyo microscope, **b** Hommel surface roughness tester T500, **c** KW 6305 power measuring device, and **d** Kistler quartz three-component dynamometer

Table 4 Values of machinability indicators

Machining type	*T* (mm)	*R* (µm)		*P* (kW)	*F* (N)			
		R_a	R_{max}	*P*	F_x	F_y	F_z	F_{res}
Dry	0.149 (0.033)	1.16 (0.095)	1.31 (0.28)	2.16 (0.15)	130.2 (5.3)	226.9 (14.9)	419.2 (40.2)	495.5 (26.2)
Wet	0.143 (0.007)	0.83 (0.071)	1.21 (0.24)	1.54 (0.17)	74.4 (9.6)	127.8 (7.8)	239.5 (70.7)	283.8 (61.9)
MQL	0.081 (0.004)	0.64 (0.166)	1.08 (0.18)	1.05 (0.09)	46.1 (3.9)	82.6 (2.2)	96.1 (4.1)	134.9 (5.6)

Fig. 7 A comparison of tool wear (flank wear) for the cooling/lubrication strategies



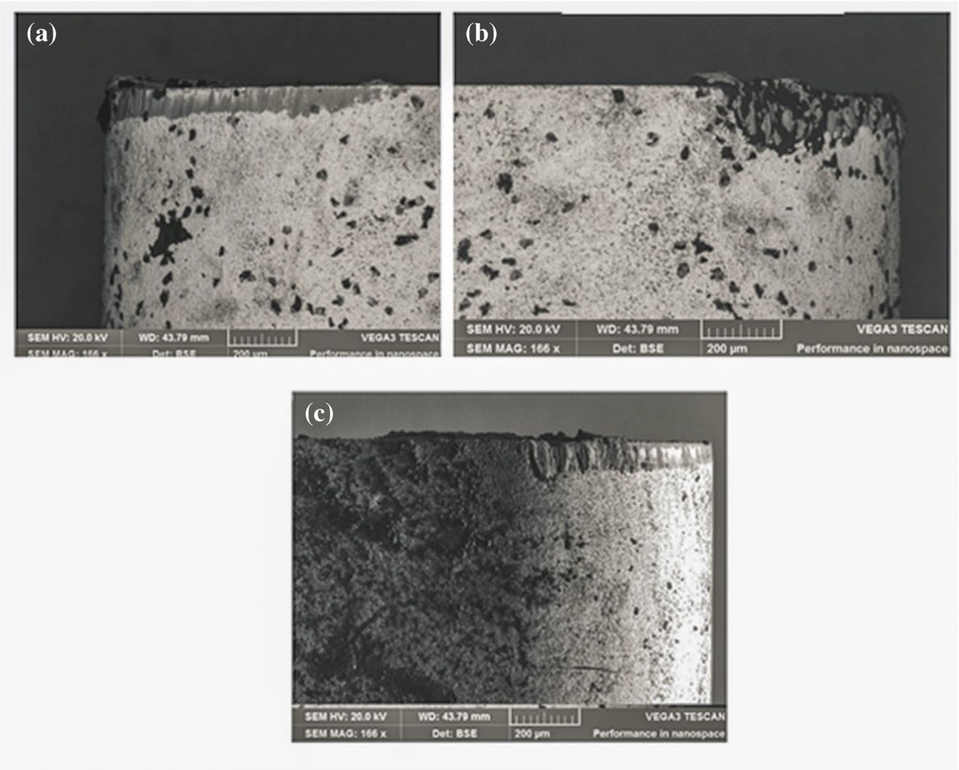
strategies are presented in Fig. 7. The highest average flank wear of 0.149 mm was recorded for dry machining. Wet machining produced similar flank wear albeit slightly smaller at 0.143 mm. Flank wear was significantly less for MQL machining at 0.081 mm. These results indicate that the lubrication/cooling technique may have a significant influence on tool life.

A more detailed study of the tool wear modes via scanning electron microscopy shows that machining at high speeds during MQL machining produced abrasive type wear (Fig. 8a), whereas for dry machining, built-up edge formation and adhesive wear is more prominent (Fig. 8b). Wet machining looks like a mixture of abrasive and adhesive wear (Fig. 8c). As expected, the flank wear for dry machining is highest because of the absence of any cooling/lubrication and friction therefore causing high temperatures in the cutting interface.

3.2 Effect of lubrication techniques on surface roughness

Theoretically, the turning process surface roughness is a function of tool nose radius and feed rate only. In practice, it may also be an indicator of tool condition which include tool wear, tool breakage, alignment, and mounting stiffness. These can be noticeable in the surface roughness profile of the workpiece after machining [16]. Benardos and Vosniakos [17] investigated several techniques to keep track of the

Fig. 8 SEM images: **a** MQL machining, **b** dry machining, and **c** wet machining



surface roughness of a workpiece and how surface roughness has a direct and indirect relationship with tool geometry/wear, tool vibration, cutting force, and power consumption.

Figure 9 presents a comparison of the arithmetical mean roughness value (R_a) for the different lubrication/cooling strategies. The best (lowest) roughness was obtained with MQL machining. Wet machining was second, while the poorest (highest) roughness was demonstrated with dry machining. It was also found that the improved surface roughness associated with MQL and wet machining were as a result of the lower prevalence of adhesion and built-up edge formation at the tool. Dhar et al. [18] indicated that an increase of surface roughness can also be directly related to increased flank wear. Surface roughness values were reduced in both wet and MQL machining. This was attributed to the low auxiliary flank and notch wear on the auxiliary cutting edge.

3.3 Effect of cooling techniques on cutting force

Figure 10 demonstrates that the cooling/lubrication strategy may have a dramatic effect of the cutting force. Machining by MQL demonstrated a significantly lower cutting force than dry cutting (134 N versus 495 N) with wet machining in between (283 N). The reduced cutting forces demonstrated during MQL-assisted machining is due to MQL's effective injection of lubricant in between the tool and workpiece interface by the penetration of micro-droplets of lubricant supplied at optimum flow rate and air pressure to the machining zone which results in minimized friction and thereby cutting forces. This reduction in friction also has a beneficial effect on tool wear and its subsequent secondary effects. Cutting forces are directly proportional to tool wear [19]. Typically, when tool wear increases, the friction will increase and cutting forces will begin to increase. This may be an effective way to monitor tool condition.

3.4 Effect of lubrication techniques on power consumption

Figure 11 presents a comparison of power consumption as a function of lubricant/cooling strategy. MQL-assisted machining demonstrated the lowest power in contrast to both dry and wet machining. This mostly due to the significantly lower cutting forces and not needing to pump copious amounts of lubricant as required for wet/flood cooling. Even though dry machining requires the least amount of power for running ancillary systems, it demonstrates the largest power consumption due the significantly higher cutting forces.

Fig. 9 A comparison of surface roughness for the different cooling/lubrication strategies

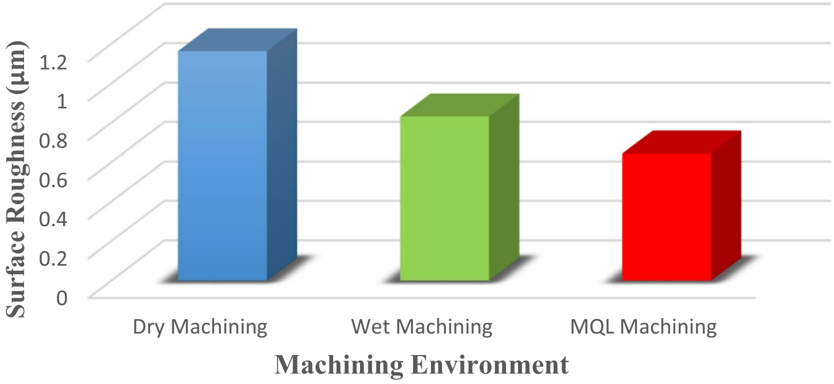
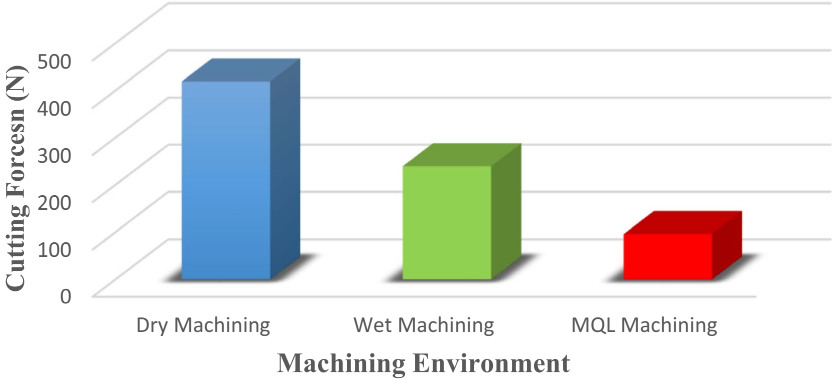


Fig. 10 A comparison of cutting forces for the different cooling/lubrication strategies



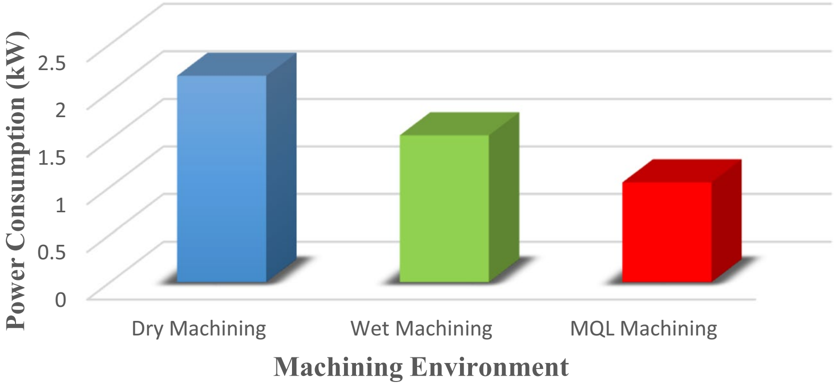


Fig. 11 A comparison of Power consumption for the different cooling/lubrication strategies

3.5 Effect of lubrication techniques on chip morphology

Chip morphology is the result of specific chip formation mechanism(s) occurring during machining. It indicates several significant aspects of the actual machining conditions [20]. Dyami and Salem et al. [21, 22] indicated that the size, shape, color, and thickness of chips are good indications of the machining strategy utilized [23]. They recommend avoiding the long chip formation to prevent subsequent entanglements around the workpiece and avoid machine tool damage. Figure 12 presents a visual comparison of chip shape, size, and patterns for the different cooling/lubrication strategies investigated in the current investigation. A significant variation is evident; MQL chips are snarled/ribbon-shaped and have brighter and smoother rear surfaces. It indicates that chip separation and lifting took place effectively in the case of MQL. MQL efficiently penetrated the tool-chip interface with micro-droplets of lubricant to induce a cushion-like arrangement and consequently reducing the cutting temperature and reducing/eliminating built-up edge formation.

Dry machining resulted in tubular or helical-shaped chips that displayed significant discoloration due to being subjected to high temperatures. Frequent chip entanglements due to the elongated chip length were also evident. The high cutting temperatures associated with dry machining also resulted in chip adhesion.

Wet machining produced, spiral-shaped lightly discolored chips. Because of the less intense cutting temperature produced during wet machining in contrast to dry machining, the chips produced were deemed to be much better than the ones produced under dry machining condition. The overall chip length produced under wet machining condition was shorter than dry machining chips.

Snarled or ribbon-shaped chips were produced during MQL machining. This was caused by MQL's ability to be directly supplied on the rake face, which enables the coolant to infiltrate in-between the tool-chip interfaces. This aided separation and upliftment of the chips from the rake surface. Although the chip geometry was similar to the chips produced by wet machining, the rear surface was smoother and mostly devoid of discoloration indicating an auspicious chip-tool interaction with less built-up edge formation and lower temperatures.

As far as chip morphology is concerned, all three cooling/lubrication techniques resulted in serrated chips. Serrated chips occur due to inhomogeneous deformation because of the interaction of extreme cutting interface temperature and the low thermal conductivity associated with titanium alloys [24]. Moreover, the segmentation of the chips occurred due to crack-shear banding (see Fig. 13), where a crack and an adiabatic shear band (ABS) are visible between two consecutive chip peaks. The cutting temperature and the amount of deformation induced on the primary shear zone both are responsible

Fig. 12 Comparison of chip shape for dry, wet, and MQL machining

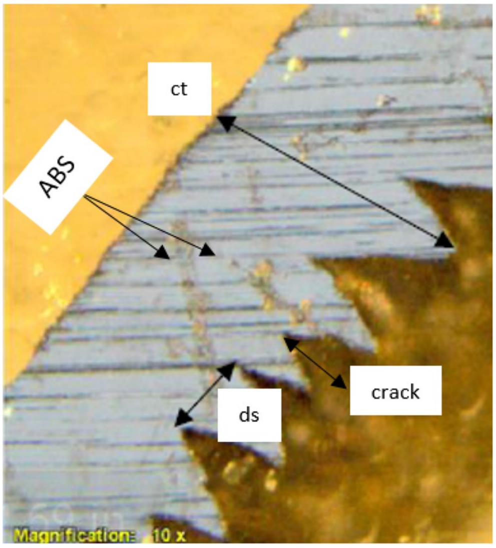


Fig. 13 Cross-section of the chip generated

for increasing the chip segmentation mechanism during the machining of titanium [25].

A detailed chip morphology investigation was conducted. Figure 13 presents a typical cross-sectional view of a chip. It presents the location of the adiabatic shear bands (ABS) and the crack initiation points along with the chip thickness (ct) and the serration pitch (ds).

Figures 14 and 15 present comparisons of chip thickness and serration pitch as a result of the three-machining environment. MQL machining demonstrated the lowest chip thickness and serration pitch, whereas dry machining was the highest in both cases. Typically, thinner chips with reduced serration pitch are desirable for improved cooling due to the screening effect of the thicker chips on the external coolant/lubricant application. Improved cooling implies less coolant/lubricant use which is beneficial for sustainability. In addition, shorter chips are suitable for recycling or disposing of.

4 Conclusions

Although MQL has been applied to various high strength titanium alloys, i.e., Ti6Al4V, very little work has been done in relation to the commercially pure grades, i.e., grades 2 and 4. The novelty of the work lies in the application to grade 4 and specifically showing that in most cases, a similar or superior machined part surface integrity may be achieved at significantly reduced power and lubricant consumption which has real benefits as regard to sustainable

Fig. 14 A comparison of chip thickness for the different cooling/lubrication strategies

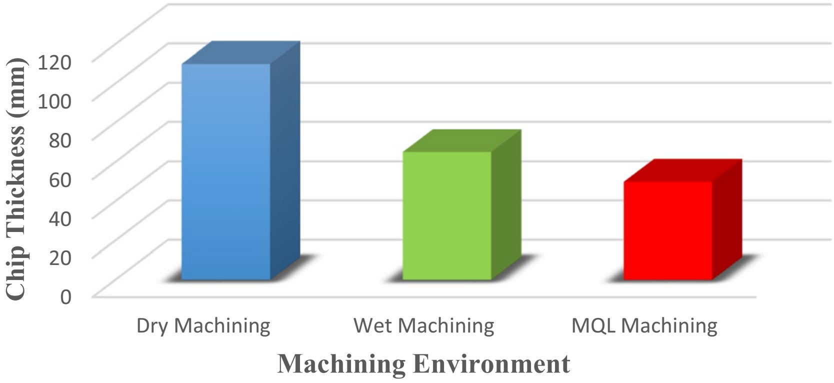
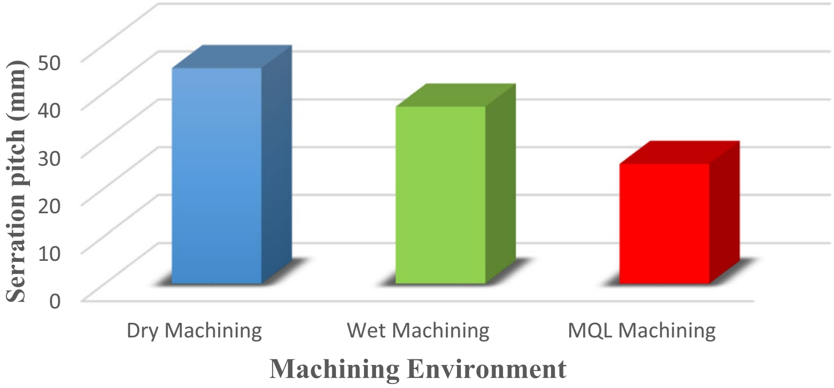


Fig. 15 A comparison of the serration pitch as a function of machining environment



manufacturing. To this end, various machining descriptors that may have a significant influence on sustainable machining are evaluated for MQL machining and directly in contrast to dry and wet machining.

The following conclusions can be made:

(i) Optimized MQL machining demonstrated improved tool wear, lower cutting forces, lower power consumption, and lower chip thickness and serration pitch. This implies lower cost, lower energy use, and a dramatically lower consumption of coolant/lubricant which are all beneficial for improved sustainable manufacturing.
(ii) The improvements mentioned above for MQL machining is realized while demonstrating an overall improvement in surface finish while maintaining an acceptable chip shape.
(iii) The benefits realized by optimized MQL machining are due to the improved lubrication and direct cooling in the tool chip interface that reduces friction, cutting temperature, built up edge, and chemical interaction with the tool.

However, there are still difficulties to overcome and important factors to consider while implementing MQL machining, despite the advantages and prospects it can provide:

Regulatory and safety concerns: Some industries, such as aerospace or medical device manufacturing, have stringent regulations and standards related to machining processes and the use of lubricants. Implementing MQL may require validation and compliance with these regulations, which can add complexity and time to the adoption process. Safety considerations, such as the potential for increased fire hazards due to the reduced amount of lubricant, can also be a concern in certain environments.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Thabo Nelson Mathonsi and Rudolph Frans Laubscher. The first draft of the manuscript was written by Thabo Nelson Mathonsi, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by University of Johannesburg.

Declarations

Competing interests The authors declare no competing interests.

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